EFFICIENT LIGHT COUPLING TO PLASMONIC NANOANTENNAS VIA OPTIMIZING THE NEAR-FIELD POLARIZATION DISTRIBUTION

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ASTC Interest Area: Near-Field Transducer Metrology

Abstract: Plasmonic nanoantennas have found recent use as near-field transducers (NFTs) in heat assisted magnetic recording (HAMR). A critical component to their efficiency as NFTs is that the applied electric field (or polarization) of the light be precisely aligned with the apex of the sharp tips comprising the nanoantennas. However, a tip may not be perfectly fabricated and as such its apex may not be normal to the surface of the recording medium. Moreover, future nanoantenna design alternatives may require that the applied electric field be oriented in a general direction in three-dimensional space. Therefore, the long-term objective of the proposed research is to facilitate the optimization of light coupling to NFTs. The 1-year pilot study will lay the groundwork for this by developing appropriate methods to efficiently align the input optical polarization to a plasmonic nanoantenna located in the focal plane of a strongly focusing optical system. This will be achieved by exercising full control of the near-field optical polarization distribution in three spatial dimensions, and by measuring the response of a near-field antenna excited by such a field. To this end, the PI has previously developed the theory for achieving 3D polarization control with relatively high efficiency, without the use of any polarization optics. Specifically, the polarization at the focal spot of a strongly focusing system is tuned through modifying the scalar complex field distribution of the input light. Three low-order azimuthal spatial harmonics have been identified to each produce a focused linearly polarized component. Thus, controlling the relative complex weights of these azimuthal harmonics, which in the proposed work will be done using low-cost liquid crystal display technology, generates any desired 3D state of polarization. In addition, a recently proposed method of using the dipolar response of a nanoparticle to measure the 3D polarization state of strongly focused unpolarized light will be adapted to map the polarization response of a nanoantenna. For this pilot study, the 2D waveguide (e.g., planar solid immersion mirror) used in HAMR to create a tightly focused longitudinal field at the NFT will be replaced by a high-numerical-aperture (NA) objective lens (typically NA ~ 1.3-1.4) and various nanoantenna designs will be explored to test the proposed methodology. The project deliverables include: 1) a method to convert a standard laser-illuminated inverted microscope to a NFT metrology platform capable of determining the optimum field distribution for an NFT; and 2) a Matlab graphical user-interface to facilitate analysis.

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I. SUBJECT OF RESEARCH AND RELEVANCE TO ISSUE(S) TO BE SOLVED

A. Motivation

Metal antennas at the nanoscale (or plasmonic nanoantennas) are of growing interest because of the resulting sub-diffraction-limit spatial confinement of an incident optical field [1]. Moreover such confinement in a given spatial mode is known to result in an increased energy density, or local field enhancement, of the applied optical (electric) field at sub-wavelength scales, especially when the incident optical frequency is resonant with the nanoantenna surface plasmon resonance. Efficient nanoantenna designs have incorporated sharp tips in their geometries to make use of a lightning rod effect [1]. Potential applications of this technology range from super-resolution imaging to single-molecule detection as well as fundamental studies of nonlinear optical phenomena [2]. Yet another application has been found in heat assisted magnetic recording (HAMR) [3]. In this case, the nanoantenna is used as a transducer whereby incident optical power funneled to a sub-diffraction spot in a magnetic medium is converted to heat to permit magnetic writing of data. With such promising applications, it is critical that the applied optical field be efficiently coupled to the nanoantenna. Within the dipole approximation [1], this requires that the incident electric field of the light be precisely aligned with the apex of the nanoantenna tip. This is the reason why optical beams that generate enhanced longitudinal focal fields are preferred in these instances. Typically, this is achieved by employing a radially polarized beam [4] as input to a high-numerical-aperture (NA) lens, or, in the case of HAMR, a planar solid immersion mirror (PSIM) is used to obtain the planar equivalent of a radially polarized beam [3]. However, either imperfections in fabrication or deliberate design alternatives of nanoantennas may require electric-field components with projections in the x-z or y-z plane, for example, where the z axis is parallel to the optical propagation direction. Thus, full control of the optical polarization along three spatial dimensions in the near field would be critical to efficient coupling to any nanoantenna. Concomitant with this, it becomes necessary to confirm the state of 3D polarization in the near field. Both of these tasks will be addressed in the proposed research.

B. Goals, Tasks, and Deliverables

The principal objective of the proposed 1-year pilot study is to develop a near-field transducer (NFT) metrology platform that will determine the required near-field polarization distribution for optimal coupling to a plasmonic nanoantenna. Successful determination of the required optical field for efficient coupling to a nanoantenna will enable improvement of the current PSIM design used in HAMR, and more generally, permit the exploration of future designs for integrated focusing elements and NFTs. The specific research tasks to be achieved are: 1) to provide a low-cost method for generating a desired 3D polarization state in the near field; and 2) to determine the near-field polarization distribution using far-field measurements. Project deliverables will include: 1) a method to convert a standard laser-illuminated inverted microscope to a NFT metrology platform; and 2) a Matlab graphical user-interface to facilitate analysis (the PI has experience developing such GUIs [5]). The effectiveness of the approach will be tested on nanoantenna samples obtained from ASTC consortium members, as well as various types of nanoantennas fabricated by the PI’s research group (see Ref. [2] for example of bowtie nanoantenna).
C. Approach

The proposed work can be considered in 3 parts: generating arbitrary polarization control in 3D in the near field, measuring the near-field polarization distribution, and determining the polarization response from a nanoantenna. First, an optical probe will be configured to produce a general 3D state of polarization in the near field. Next, a polarization detection method will be applied to optimize the desired near-field polarization distribution generated by the optical probe. Finally, the first two steps will be used to map the polarization response from the nanoantenna under study. The ability to sweep the electric field direction of the optical probe in a general way will allow one to determine the optimal near-field polarization distribution for efficient field coupling to an NFT. It should be noted that, in general, optimal coupling to an NFT, such as the type used in HAMR, will also be a function of input optical wavelength and the grating (condenser) design. This pilot study tackles the optical field alignment problem, knowledge of which will facilitate NFT design.

D. Generating an Arbitrary 3D State of Polarization in the Near Field

The polarization of light is the locus of its electric-field vector over time. In general, since the electric field can have three orthogonal components, the locus will be an ellipse oriented in three spatial dimensions [6]. Although controlling the 3D nature of this polarization would be useful to many fields of science and technology [6], there has been limited research progress in this area. One notable exception has been the study of radially polarized vector beams, which when focused are expected to yield varying amount of x, y and z polarization components of the electric field based on the strength of focusing used [7]. However, the type of control that this technique permits is fairly limited since the individual orthogonal polarization components cannot be independently tuned. In recent years, the PI proposed an approach to access the complete 3D nature of the optical polarization [6].

The technique consists of generating beams whose transverse electric-field distribution can be described by an equation of the form

$$\Lambda(\alpha, \beta) = \Gamma(\alpha)\Lambda(\beta)$$

separable in the radial and azimuthal directions, corresponding to the angles $\alpha$ and $\beta$, respectively. It was shown that the azimuthal component can be represented by a spatial harmonic decomposition. More importantly, it was proven that three of the low-order azimuthal harmonic components comprising a field with input azimuthal distribution

$$\Lambda(\beta) = \tilde{\Lambda} + S_x \sin 2\beta + C_y \cos \beta$$

provide direct control of the 3D polarization distribution in the near field. Specifically, controlling the relative complex weights of these azimuthal harmonics generates any desired 3D state of polarization. An example of this is shown in the simulation results in Fig. 1. In this case, the input-field distributions are designed to produce the following desired 3D states of polarization at the focal spot: amplitude and phase distributions of the $x$-polarized input field needed to produce Fig. 1(a) $45^\circ$ linear polarization in the $x$-$z$ plane, and Fig. 1(b)

![Figure 1](image-url)
elliptical polarization in the $y$-$z$ plane. Interestingly, it was also found that the radial component $\Gamma(\alpha)$ determines the spatial resolution on-axis at the focus. The fact that the resolution and polarization can be controlled independently is a salient advantage of this technique.

As can be expected, shaping the azimuthal harmonics requires both phase and amplitude control of the optical field, which can be achieved using a pair of spatial light modulators (SLMs). However, the SLMs currently available on the market are expensive. A cheaper alternative is to use the LCD panels salvaged from commercial electronic projectors, which are on average an order of magnitude cheaper than SLMs. Modern projectors come with three LCD panels, one for each RGB channel. Still the challenge is that these LCD panels are effectively sandwiched between two linear polarizers in order function as amplitude-only modulators of the light. For the aforementioned proposed tasks, these LCD panels will need to be adapted to also serve as phase modulators. Fortunately there is an approach to achieve this.

Functionally an LCD panel behaves as a voltage dependent polarization wave retarder followed by a voltage dependent rotator [8-10]. Generally, for a given input polarization, each element of an LCD panel would yield an output polarization corresponding to the control voltage applied to it—making it difficult to change the phase of the light without changing its amplitude. Fortunately, it turns out that for select input polarization states the output polarization state as a function of voltage resides in the vicinity of a meridian on the Poincare sphere [8-11], i.e., equiazimuth polarization states are generated. These states can be converted to linear polarization states with the same intensity but different phase using a properly oriented quarter-wave plate (QWP) which can collapse any point on a meridian on the Poincare sphere to a single point on the equator but with different phase [10]. The end result is the ability to achieve separate phase and amplitude control of the input light. Figure 2 is an example experimental schematic for 3D polarization control. The polarization elements surrounding the two LCD panels are used to achieve the aforementioned phase and amplitude control. The PI’s lab has already obtained preliminary data demonstrating this effect (see Fig 3).

**FIG. 2.** Experimental setup for implementing 3D polarization at the focus of an objective lens. The quarter-wave plate (QWP), half-wave plate (HWP), and polarizers are used to convert each computer-controlled LCD device to respective phase and amplitude modulators.
E. Detecting the 3D State of Polarization

The method for generating arbitrary 3D polarization in the focal field was discussed above. Now the task at hand is to confirm the state of this near-field polarization distribution. Generally, the standard 2D state of polarization is directly measured using linear polarizers and quarter-wave plates. However, measuring the 3D state of polarization in the near field is much more challenging, and a model based approach has to be employed. In the proposed work, a recently demonstrated method of using the dipolar response of a spherical nanoparticle to measure the 3D polarization state of strongly focused unpolarized light will be adapted.

FIG. 3. Normalized transmitted intensity as a function of control voltage. In commercial electronic projectors the LCD panels are used to modulate the amplitude of the transmitted light. However, with the appropriate optical setup, these panels can be used to generate phase only modulation where the transmitted intensity remains constant with control voltage.

The proposed experimental setup for measuring the 3D polarization distribution in the near field is shown in Fig. 3. Light is focused onto a spherical gold nanoparticle with its diameter much smaller than the wavelength of the light being used. Because of the small size, a dipole moment is induced on the particle which is proportional to the strength of the field at the position of the nanoparticle [12, 13]. The scattered field is then collimated. The collimated electrical field $E'$ can be related to the scattered field $E$, hence to the induced dipole strength or the local field, by [12, 14],

$$E'(r', r) = A(r', r) E(r),$$

where $A$ is a geometry dependent matrix relating the scattered field from the nanoparticle to detected field, $r$ is a vector relating to a point in the vicinity of the nanoparticle, and $r'$ is a vector relating to a
point on a position sensitive detector, e.g., a CCD camera. The Stokes vector of the scattered field is then measured at a CCD using a QWP and a polarizer [15]. The position sensitive Stokes vector can then be used to generate the coherency matrix $\Phi_{2D}$, a convenient representation of the measured polarization distribution at the detector. More importantly, $\Phi_{2D}$ can be related to the polarization distribution $\Phi_{3D}$ of the field at the nanoparticle using the relation

$$\Phi_{2D}(r', r, \omega) = A(r', r)\Phi_{3D}(r, \omega)A^T(r', r).$$  (4)
II. RESOURCES REQUIRED TO PERFORM PROJECT

The following summarizes the required resources for the project. Additional details are provided in the budget.

A. Personnel

Funding is requested for one-month summer salary support for the PI (Toussaint) who will supervise and lead the project. Additional salary support is requested for one graduate student (25% appointment during the academic year and 25% appointment for one summer month) to carry out optical experiments and modeling.

B. Equipment

Successful completion of the project will require the purchase of an electron multiplying CCD (EMCCD) camera (e.g., Andor OAT-LUCA-R) to achieve photon sensitive measurements, and some basic optical/optomechanical components including mirrors, polarizers, lenses, kinematic mounts, and translation stages.

III. RESOURCES OTHER THAN ASTC FUNDING DEDICATED TO PERFORM PROJECT

The PI maintains a state-of-the-art optics laboratory of ~ 1,500 sq. ft at the University of Illinois at Urbana-Champaign. Contributed resources from the PI lab that will be applied to the project include a wavelength-tunable Ti:Sapphire laser source (Spectra-Physics Mai Tai with DeepSee, 80-Mhz repetition rate, 100-fs pulse width), a 100 mW diode laser (Newport LQC660-110C), 2 inverted microscopes (Olympus IX81 and IMT-2), an upright microscope (Olympus BX51), assorted objective lenses (Olympus with NA 0.65-1.4), a white light source (Dolan Jenner 190), a CCD spectrometer (Jobin Yvon CP140-103 and Andor iDus DU420A-BU), and a variety of spectral filters from Semrock and Chroma Technology. In addition, through the university, the PI has access to state-of-the-art cleanroom facilities (including electron-beam writing capabilities) and associated metrology tools, e.g., SEM/TEM, and AFM.

IV. RESOURCES REQUESTED FROM ASTC AND HOW THEY WILL BE UTILIZED

Expected Technical Cooperation With Sponsor(S)

As discussed in the proposal, the PI would require NFT samples from the sponsor(s) to test the proposed NFT metrology system. Sponsors’ facility utilization and student internships are not expected.

The following summarizes the required resources for the project. Additional details are provided in the budget.

Senior Personnel $10,568

Funding includes one-month summer salary support for Dr. Kimani Toussaint. Salaries are based on actual UIUC AY2011 rates and are incremented at a rate of 4.0% each year.

Other Personnel $10,605
Salary for one graduate student is included (25% appointment during the academic year and 25% appointment for one summer month). The student will carry out optical experiments that will permit characterization of the near-field polarization distribution. Salaries are based on actual UIUC AY2011 rates and are incremented at a rate of 4.0% each year.

**Fringe Benefits**

Fringe benefits are charged at a rate of 35.59% on faculty and postdoc salaries. Benefits include retirement, worker’s compensation, health, life and dental insurance, termination, and Medicare. Fringe benefits are charged at a rate of 6.36% on graduate student salaries. Benefits include worker’s compensation and health, life and dental insurance.

**Equipment**

Equipment includes the purchase of an electron multiplying CCD (EMCCD) camera (e.g., Andor OAT-LUCA-R) to achieve photon sensitive measurements, and some basic optical/optomechanical components including mirrors, polarizers, lenses, kinematic mounts, and translation stages.

**Travel**

Support for domestic travel throughout the course of the project is primarily requested for the PI to attend the approximate quarterly ASTC meetings, and potential on-site visits to the ASTC consortium member facility most aligned with the proposed NFT metrology research (e.g, Seagate or Xyrtex).

**Other Direct Costs**

Materials and Supplies: Funds budgeted for materials and supplies will cover the expendable supplies and equipment needed to conduct the research program and include items that are normally required to operate a research program. These items include, but are not limited to optical mirrors, filters, polarizers, lenses, optomechanical mounts, and translation stages, which are necessary to meet the scope of the work.

**Indirect Costs**

Indirect costs are assessed at a rate of 58.5% of Modified Total Direct Costs (MTDC). MTDC is direct costs less equipment, tuition remission, and subawards in excess of $25,000.

**V. TIMELINE**

The proposed activity is expected to take a period of at least 1 year, July 15, 2011-May 15, 2012. The development of 3D polarization control will take the first 3 months, while an additional 6 months will be spent developing the aforementioned near-field polarization detection scheme. The remaining 3 months will focus on testing the technique on various NFT samples.

**VI. HOME INSTITUTIONS & RESOURCES**

See Section III above.
VII. BIOSKETCH

Kimani C. Toussaint, Jr. is a tenure-track Assistant Professor in the Department of Mechanical Science and Engineering, and an Affiliate Faculty in the Departments of Electrical and Computer Engineering, and Bioengineering at the University of Illinois at Urbana-Champaign (UIUC). He also holds an Affiliate Faculty position in the Department of Ophthalmology at the University of Illinois at Chicago. Dr. Toussaint earned his BA from the University of Pennsylvania, and MS and PhD degrees in Electrical Engineering (specialty in quantum optics) from Boston University under the supervision of Professors Bahaa Saleh, Malvin Teich, and Alexander Sergienko. Prior to starting at UIUC, Dr. Toussaint was an NSF Minority Postdoctoral Fellow in Biology at the University of Chicago under Professor Norbert Scherer, where he worked on interference microscopy, exotic polarization states, and optical trapping.

Dr. Toussaint is a US citizen with expertise in experimental optical physics, and specializes in optical polarization studies, nonlinear optical imaging, and optical forces. Currently, he runs the laboratory for the Photonics Research of Bio/nano Environments (PROBE) at UIUC, an interdisciplinary research group that pursues problems in both nanophotonics and biophotonics. His lab pushes the limits of far-field optics through the development of a platform that fully integrates the properties of light.

Selected Recent Honors and Awards

- 8th Annual National Academies Keck Futures Initiative, 2010 [Selected as one of 150 participants in America]; 2010 NSF Faculty Early Career Development Award (CAREER); Elected to IEEE Senior Membership, 2010; National Academy of Science’s 18th Annual Kavli Frontiers of Science Symposium, 2006  [Selected as part of top 100 young scientists under 45 in America]; NSF Minority Postdoctoral Fellowship in Biology, 2005-2007
VI. REFERENCES